THE INTERACTION DYNAMICS OF PULSED RETRO-ROCKET PLUMES WITH THE GROUND DURING SPACECRAFT DESCENT ON MARS

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ABSTRACT

This study focuses on the impingement dynamics of pulsed supersonic plumes with the ground at Mars atmospheric conditions. Experimental results show that large transient pressure peaks with amplitudes between 35 and 42 kPa (4.5-5.2 psi), and durations between 10 and 18 msec develop at the surface during pulsed supersonic jet impingement at a motor frequency of 10 Hz. These transient pressure peaks are superimposed on "quasi-steady" pressure perturbations with amplitudes of about 5 kPa (0.87 psi) and duration of 55 msec. This interaction corresponds to a 20 Hz ground shock frequency. Numerical and experimental data show that the transient pressure spikes are caused by the formation and collapse of plate shocks (normal reflected shocks) due to the startup and shutdown cycle of pulse-modulated thrusters. These pressure perturbations may cause soil liquefaction and gas-soil bursting which can lead to substantial soil erosion. Our goal is to understand the dynamics of pulse jet impingement during terminal descent and quantify crater formation, dust lifting, and spacecraft stability at low ambient pressure. This study is the first step in this direction.

1. INTRODUCTION

Future landed missions to Mars and the Moon need reliable and well understood landing systems. Economical soft landing systems are important to turn the US vision for space exploration into reality [1]. The understanding of the interactions of thruster plumes with the surface, plume/thruster feedbacks caused by these interactions, and the quantification of dust lifting are important for assessments of lander stability and its contamination by dust lifted during terminal descent. Thus, these studies are extremely important not only for the engineering but also for the science of future missions [1].

Entry, descent and landing (EDL) systems have been a high risk area of landed space missions. It is extremely challenging to safely land a spacecraft in a poorly known environment. The understanding of the fluid dynamics of the impingement of thruster plumes on planetary surfaces is very important to the success of future missions. Previous investigations of plume interactions with the surface were conducted mostly by NASA researchers in the 1960s and 70s. These past studies focused on steady-state rocket plumes such as those produced by the Viking and Apollo descent engines [1]. *Studies of pulsed rocket plumes such as the ones produced by the Phoenix (PHX) spacecraft engines are virtually non-existent*. Phoenix is the first scout mission to Mars, and the first to explore its northern polar region [1]. Today's technology and analysis techniques allow us to easily study pulsed jets and expand on earlier studies of the interaction of steady-state rocket plumes with the ground. There are three main areas of concerns to mission planners related to plume-ground interaction: 1**.** Control authority deterioration; 2. Surface alteration and crater formation; and 3. Dust lifting during landing [1].

Control authority of lander's descent needs to be fully understood, so that it can be accurately included in Guidance, Navigation and Control (GNC) systems. Ground effect and lift-loss, in particular in the presence of topographical features, can cause asymmetric loadings on spacecrafts during descent [1]. This leads to undesirable torques which may cause destabilization of the spacecraft. *Rigorous GNC models of these processes for pulse-modulated thrusters during terminal descent do not exist.* In order to minimize the risks to landings, these processes must be understood and incorporated into Lander Simulators [*](LanderSim/POST) [2].The impingement of supersonic plumes with the ground can excavate the surface during landing. Once the bearing capacity of the soil is exceeded by shear stress due to plume impingement pressure perturbations, ground failure occurs [1]. This failure can lead to site-alteration, crater formation and the lifting of large quantities of sand and dust. The main reason for concern is that this may lead to lander instability, damage of its underside, and alteration of the surface of scientific interest. Dust

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lifting and settling on the lander can cause instrument contamination and failure [1]. This could also have serious effects on the overall power available to the spacecraft because of the settling of lifted dust on solar panels. *Investigations of site alteration by supersonic pulsed jets and dust lifting and deposition during spacecraft landings do not currently exist.*

The necessity for improvements in the understanding and technology of descent systems for soft Lunar and Martian landers cannot be understated. The landing ellipsis of NASA's Viking and Apollo missions was in excess of 250 km by 250 km [2]. Safe landings on scientifically interesting sites require much more precise landings. Simple and cost effective soft precision landings might be achieved with pulse-modulated engines such as the ones employed by the Phoenix spacecraft. The Phoenix engines use pulse frequency and duty cycle control to dynamically adjust thruster power during descent [3]. If these pulse-modulated engines are successful and well understood through adequate testing and modeling, they could be safely employed in future missions to the Moon, Mars and beyond.

2. EXPERIMENTAL COLD FLOW TEBSTED (CFTB)

An experimental testbed has been developed to study the impingement dynamics of supersonic pulsed jets with the surface at Mars ambient pressure (Figure 1). Various quantitative diagnostics have been installed into the CFTB to record important physical quantities. The quantitative diagnostics are composed of: 8 Freescale ground pressure sensors (with 1 msec response time and pressure range between 0 and 53 kPa), 1 OMEGA thruster Pc transducer (0-3.44 MPa), 1 MKS Baratron 627 B absolute pressure sensor (0-700 Pa), and various Analog Devices thermocouples. The ground pressure sensors and thermocouples are placed in a radial fashion along a clear acrylic impingement plate (Figure 1). To obtain supersonic flow through the nozzle, a general contour of the MR107 converging-diverging nozzles employed on the Phoenix terminal descent engines have been implemented. Half-scale model tests have been conducted to reduce the mass flow and the interactions of the thruster plumes with the chamber walls. A motor has been developed to control the pulse width (PW), thruster chamber stagnation pressure (Pc), thrust and motor frequency. Dry compressed nitrogen has been used as our test gas to simulate the specific heat ratio of hydrazine by-products. From past studies, we determined that the temperature effects are second order and do not significantly alter the flow. Past tests and numerical modeling have confirmed these results [3].

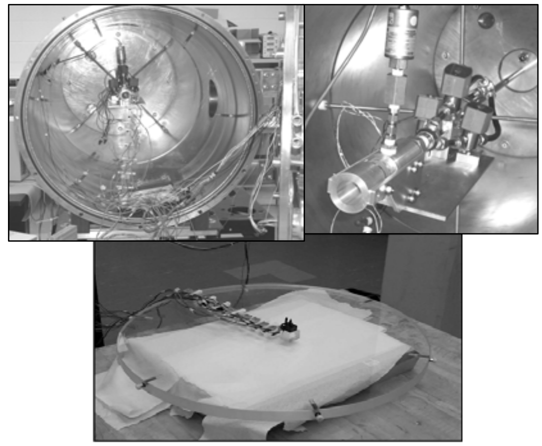

Fig. 1. Experimental Cold Flow Testbed

The test model is inserted into our Mars vacuum chamber, and its temperature and pressure are monitored. Our CFTB system has achieved all performance requirements necessary to simulate the jet plumes of the Phoenix (PHX) pulse modulated Terminal Descent Engines (TDE) (Figure 2 & Table 1). The performance requirements set by the PHX TDE during the constant velocity descent phase are: 10 Hz Pulse-Width Modulation (PWM) Frequency; 1.26 MPa maximum Pc, and 151.7 MPa/s Pc rates during engine startup/shutdown cycles. The pressure at the nozzle inlet (Pc) and the ground impingement pressures are

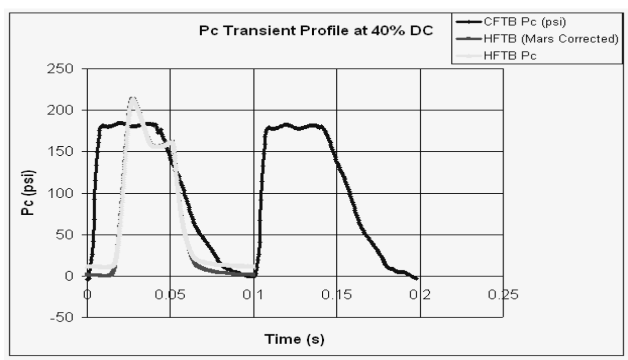

Fig. 2. CFTB-HFTB Pc profile comparison [3]

transiently monitored with a USB 6009 DAQ unit with a total sampling rate of 48 kHz. To understand the physics of plume-ground interactions for spacecraft altitudes ranging from 10 to 0.5 m from the surface, an adjustable altitude system has been developed. All hardware components have been either fabricated at the University of Michigan or obtained from commercial vendors.

Table 1. CFTB Performance Comparison

PARAMETER	CFTB	Full-Scale[4]
Nozzle Area Ratio	20.9	20.9
Pc (MPa)	1.26	1.26
Pc rise/fall time (msec)	12/25	14/18
Pulsed Frequency (Hz)	10	10
Gamma (test gas)	1.4	1.3
Tc (K)	298	1100
P ambient (Pa)	690.0	690.0
H/D Range	8.4- 21	8.4-48

3. FLOW VISUALIZATION

For transient shock structure observation, a single pass-mirror reflectance shadowgraph imaging system has been developed. The light beam passes through the vacuum chamber test section, and the beam is reflected off of a flat mirror within the chamber. To visualize the transient shock structure, a 1534 Strobotac AB that pulses the light beam at a frequency of 25 kHz has

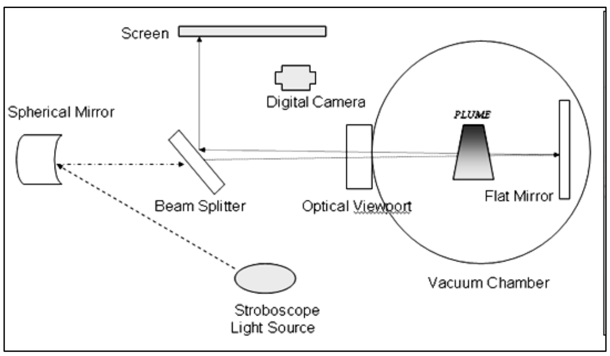

Fig. 3. Schematic of Single-Pass Reflectance Shadowgraph Imaging System [3]

been incorporated. A parabolic-mirror collimates the light beam and a 50/50 beam splitter directs the shadowgraph image on a Da-Lite High-contrast screen (Figure 3). The shadowgraph image is captured with a 7.0 MPx Nikon Digital camera.

4. COMPUTATIONAL ANALYSES

Axi-symmetric computational models have been developed for the pulsed plume-ground interactions at low ambient pressure at various altitudes in collaboration with Lockheed Martin's Aerophysics Department (LM). Both GASP (performed by LM) and FLUENT (performed by the University of Michigan) computational models were designed to study these complex flow interactions. The computational analyses done at The University of Michigan were performed at two specific heights: 0.53 meters (PHX touchdown altitude) and 1.73 meters. The Pc pressure time-series profile obtained from the PHX hot fire testbed (HFTB) was incorporated as a boundary condition to the models. The Pc pressure profiles were averaged over the 12 PHX engine tests to provide an average profile for our analyses [3]. The Pc profiles obtained from the CFTB experiments were also incorporated into the CFD models.

5. RESULTS

5.1 Pressure Measurements

Preliminary cold flow test data of experiments at Phoenix's touchdown altitude (0.53 m) of H/D=8.4, show two, centerline, transient ground pressure peaks of average amplitudes between 24 and 42 kPa, and duration ranging between 10 and 18 msec (Figure 4a and 6). This correlates to a ground shock frequency of 20 Hz. A quasi-steady state region with ground pressure amplitude of 5 kPa develops for 55 msec. Within the quasi-steady state region, we observe minor pressure perturbations with frequencies ranging between 0.5 and 1.8 kHz. We also observe these transient pressure spikes at higher altitudes where H/D=11.98 (0.762 m), but with smaller amplitudes. The maximum pressure peak have amplitudes between 22 and 26 kPa with duration of approximately 10-18 msec and a quasi-steady pressure amplitude of 4.4 kPa for 40 msec [5].

Ground pressure profiles were also modeled by CFD, and the results were compared with the experimental results (Figure 7).

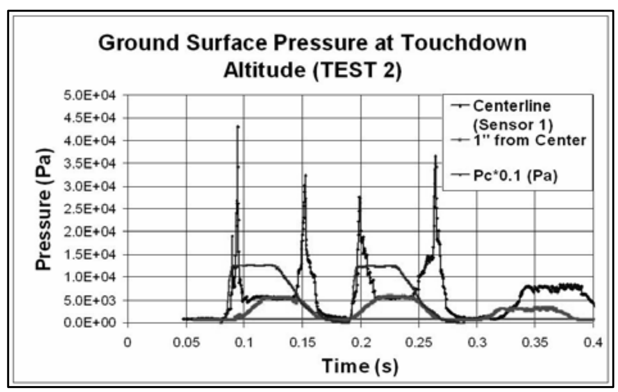

Fig 4a. Experimental ground pressure/Pc temporal profiles at touchdown altitude [5]

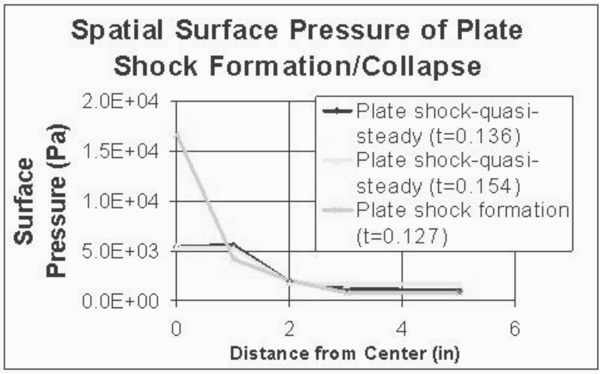

Fig. 4b. Experimental spatial pressure profile at touchdown altitude [5]

During plate shock formation, the centerline pressure amplitude is 15 kPa and at quasi-steady state regime, the pressure amplitude decreases to 5 kPa (Figure 4b). From the surface pressure profile graph at quasi-steady state regime (t=0.136s), two small characteristic ground pressure peaks of 5.54 kPa are observed at +/- 0.8 D_e (nozzle exit diameter) (Figure 4b). Higher spatial resolution is required.

5.2 Flow Visualization Data

Near-field flow visualization of cold, steady-state supersonic jets produced by the PHX thruster have been obtained (Figure 5). However, the visualization of shock-ground interactions caused by pulsed, under-expanded jets is still in progress. *Our main goal is to visualize the plate shock formation/collapse dynamics seen in the numerical simulations.*

Numerical simulations of the transient plume shock structure at 1.73 m provide us with an initial model of the ground interaction physics.

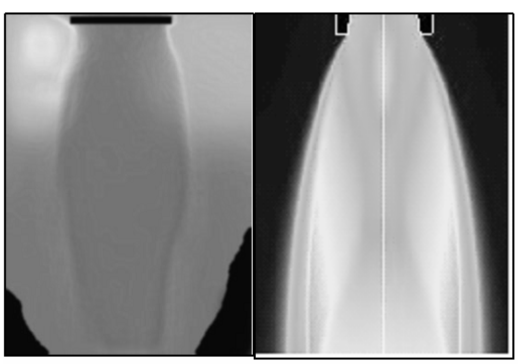

Fig. 5. Shadowgraph (LEFT) and CFD (RIGHT) near-field flow comparison [5]

6. DISCUSSION

6.1 Transient Ground Pressure Profile Analyses

There is close agreement between Pc and the rate of change of Pc in transient profiles obtained with the HFTB and our CFTB, with a PWM of 40 msec (Figure 2). Water-hammering effects at the TDE valves cause an asymmetric double pressure peak at 50 msec in the HFTB data [2]. During cold flow testing, water hammer effects were negligible. This causes a slight disparity in the data from these two tests (Figure 2).

CFD studies show that ground pressure peaks are caused by the formation and collapse of a plate shock. These processes are caused by the engine's startup and shutdown cycle. The transient peaks form when an under-expanded shock wave strikes the surface. When the wave is reflected by the surface, a plate shock parallel to the ground plane forms [7]. When the nozzle chamber pressure cannot provide the energy necessary to sustain the plate shock, it collapses. Our CFD simulations show that the maximum diameter of the plate shock is approximately 1.25 D_e (nozzle exit diameter). The plate shock is a convex structure at a standoff distance of 0.23 times the nozzle altitude (Figure 7). We believe that the amplitude of the pressure peaks depend on the rise/fall rate of the thruster chamber pressure (Pc), the plate shock strength (Mach number), and the thruster altitude. The spreading of these transient peaks may be related to the Pc rise/fall times. The amplitude of the quasi-steady state ground pressure profile may depend on the ambient pressure, the nozzle altitude, and the strength of the plate shock. High frequency pressure oscillations develop during the quasi-steady regime, because of fluctuations in the plate shock perpendicular to the ground (Figure 6) [7]. These oscillations are caused by Hartman's fundamental modes [6]. The flow physics in the impingement zone is quite unsteady [7]. There is good agreement between CFD and experimental data of these transient processes (Figure 6).

In preliminary studies of steady state under-expanded jets, under similar boundary conditions, the ground pressure is approximately constant with time with only minor oscillations of amplitude +/-0.05% of Pc. No transient pressure spikes were noticed during steady-state flow testing.

6.2 Spatial Ground Pressure Profile Analyses

The spatial pressure profiles at the centerline and the point 1 inch adjacent to it show different pressure profiles during normal shock formation and the quasi-steady state regime (Figure 4b). This same behavior is observed during plate shock collapse. A decrease in ground pressure is observed after shock formation. This may be caused by flow recirculation in the post-shock regime. The generation of the stagnation bubble produces small-scale spatial pressure variations in the quasi-steady state flow at the external boundaries of the plate shock (Figure 4b) [7].

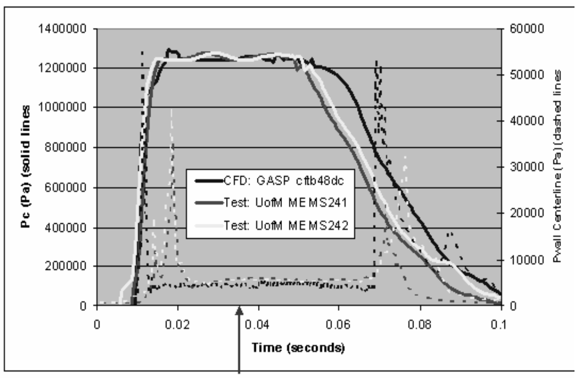

Fig. 6. LM CFD & UM test data comparison [5]

6.3 Flow Structure Analyses

Preliminary shadowgraph images confirmed that our laboratory system produces the desired supersonic plumes and has the flow visualization capabilities necessary for studying the dynamics of jet impingement. Preliminary shadowgraph images are comparable with results from CFD simulations (Figure 5). It shows that the jet is moderately under-expanded with an expansion ratio of approximately 4.2. The expansion ratio is determined by the ratio of ambient pressure to nozzle exit pressure. According to one-dimensional nozzle theory, the PHX nozzle exit Mach number is 4.5 and the exit pressure is 2.8 kPa for both the sub-scale cold flow test model and full-scale TDE. Further optimization is necessary to improve the flow visualization such as time synchronization of the image with cycling of the motor valve. We are currently increasing the field of view of our shadowgraph system to capture both the near-field flow and the plate boundary interaction.

The plume structure is collimated (Figure 7). This occurs because the Mars back pressure (ambient pressure) is relatively large. The plume structure for a lunar spacecraft during terminal descent has a larger plume diameter and expansion ratio because of the low back pressure (the near vacuum lunar atmosphere) [8].

After the jet impinges on the surface, it diverges in a radial fashion at speeds of Mach 2.1 (Figure 7). This high speed wall jet causes significant increase in the shear stress at the surface that can lead to large ground erosions.

7. FUTURE WORK

This study will provide data for accurate characterization of the ground interaction physics due to pulsed jet impingement in support of the Phoenix EDL Validation and Verification Program. It will also help the Phoenix Science Team and future NASA mission planners understand the potential contamination and site-alteration problems caused by dust lifting during landing, and if necessary it will help the team develop mitigating strategies for reducing the effects of pulsed rocket plume-soil interaction [3]. The main goals of this investigation are:

1. To provide physical and analytical models that can be used to predict the effects of plume-soil and plume-surface interactions.
2. To determine the ground pressure profiles and ground site-alteration as a function of altitude and soil properties, as well as the conditions that leads to soil liquefaction and gas-soil bursting.
3. To quantify dust particle lifting as a function of plume and soil characteristics.
4. To study the effects of terrain asymmetry such as slopes and idealized craters on surface-plume interaction.
5. To develop shadowgraph/Schlieren images of transient pulsed jets for model validation.

7.1 Phase I: Plume-Surface Interaction Dynamics

We are currently in the initial stages of optimizing our shadowgraph system to visualize the plume shock structure during pulsed firing. Our goal is to develop a system capable of characterizing flow impingement via transient pressure measurements at the ground plane and visualizations of the shock-ground interaction. In particular, we plan to determine the dynamics of vortices formed between the free stream shock structure and the wall jet. We will use a Particle Image Velocimetry (PIV) available to our group to study the behavior of these vortices and their impact on dust particle transport. This approach will provide us with

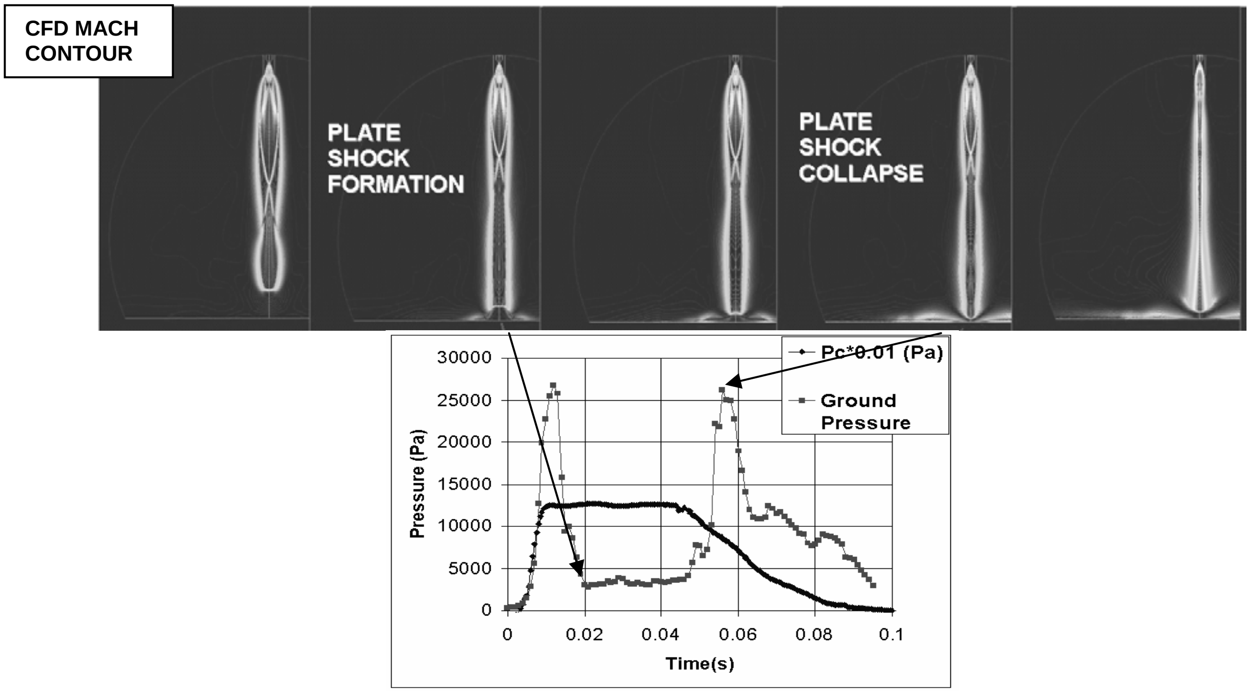

Fig. 7. Plate shock formation-collapse processes for a full-scale PHX TDE at 1.73 m altitude [5]

quantitative and qualitative data on pressure impingement, plume structure, and dust particle transport.

7.2 Phase II: Plume-Soil Interaction Dynamics

Once we complete the studies of pulsed supersonic jet impingement, we plan to study the effects of pulsed rocket exhaust on simulated Martian and lunar soils at NASA-Ames Planetary Aeolian Laboratory (PAL) and possibly at NASA-JPL [5]. Currently, we are working on the preliminary design of these experiments with other Phoenix Team members. The main goal of this second phase is to study the effects of transient perturbations on "cratering" and dust lifting. An important concern is that soil liquefaction may occur because of high pressure ground disturbances caused by the pulsed jets. Ground shock vibrations caused by large pressure perturbations may disrupt the soil and reduce particle-to-particle cohesive forces. This decreases the bearing capacity of the soil and eventually may lead to ground failure and crater formation [9]. The extent of ground failure is dependent on non-linear interactions between the jet plume and the ground as well as the soil's physical properties [9]. We have matched the pressure footprint and the exhaust flow field with full-scale TDE, but non-dimensional analysis is necessary to study the dynamics of plume-soil interactions. The non-dimensional parameters that need to be similar in both the CFTB and the full scale models are: hypersonic similarity term, aerodynamic to soil restraining shear stress ratio, density ratio of testgas to soil, and Reynolds/Froude number. This analysis will allow us to build simple scaling models of soil excavation and dust lifting due to pulsed rocket plumes.

8. CONCLUSION

From CFTB and CFD data that match the characteristics of the Phoenix MR107 motor, we observe a ground shock frequency of 20 Hz with maximum average pressure amplitudes of 35 kPa and an average "quasi-steady" pressure perturbation of 5.0 kPa near touchdown altitudes. *Experimental and computational data show good agreement with each other.* The large pressure amplitudes are strongly correlated to the plate shock formation and collapse processes of an under-expanded jet. These events have been observed to take place between altitudes of 1.73 m and 0.53 m, but further studies at higher altitudes are still necessary. The ground shock perturbations may cause soil liquefaction and gas-soil bursting which could lead to large lateral ground erosion and an increase in the amount of dust lifting.

9. ACKNOWLEDGEMENTS

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